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Progressive Damage, Fracture Predictions, and Post Mortem Correlations for Fiber Composites

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PROGRESSIVE DAMAGE, FRACTURE PREDICTIONS, AND POST MORTEM CORRELATIONS FOR FIBER COMPOSITES

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SUMMARY

Lewis Research Center is involved in the development of computational mechanics methods for predicting the structural behavior and response of composite structures. In conjunction with the analytical methods development, experimental programs including post failure examination have been conducted to study various factors affecting composite fracture such as laminate thickness effects, ply configuration, and notch sensitivity. Results have indicated that the analytical capabilities incorporated in the CODSTRAN computer code are effective in predicting the progressive damage and fracture of composite structures. In addition, the results being generated are establishing a data base which will aid in the characterization of composite fracture.

INTRODUCTION

The ability to design complex composite components and structures for both aeronautical and space applications requires a working knowledge of several disciplines. In an effort to characterize composite fracture, at Lewis Research Center, several disciplines were employed including: (1) an extensive experimental program with a unique RUSCAN (Real-Time Ultrasonic C-Scan) facility, (2) post failure analysis with a scanning electron microscope (SEM), and (3) analysis methods in the CODSTRAN (COmposite Durability STRuctural ANalysis) computer code (ref. 1). The data provided by RUSCAN AND SEM were used to verify the progressive damage and fracture predictions by CODSTRAN.

CODSTRAN incorporates a constituent material property databank, composite micro and macromechanics, finite element analysis, and failure criteria modules to predict progressive damage and fracture loads of fibrous composite structures. In its prediction of progressive fracture, CODSTRAN identifies damage occurring at the microstructural level through the application of an iterative scheme described in detail below. Ultimately, CODSTRAN yields fracture load and mode predictions.

The material system selected for testing and analysis in the composite fracture characterization program was graphite fiber/epoxy resin. Understanding the significant factors affecting composite (graphite/epoxy) fracture including ply layup, laminate thickness, and notch sensitivity became the impetus for the several experimental programs which will be discussed.

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These same factors were modeled in the CODSTRAN program and their effects on fracture behavior were documented. Finally, and most importantly, the capability for using the data generated from the post failure analysis of the fracture surfaces in verifying and corroborating the measured and predicted results were demonstrated.

EXPERIMENTAL PROGRAM

The first experimental program that significantly contributed to the data base of the composite fracture characterization study was conducted in 1977. The objective was to study the mechanical behavior and fracture characteristics of unidirectional, high-modulus, graphite fiber composites subjected to off-axis tensile loads (ref. 2). The specimens were fabricated from Modmor I - graphite fibers in a matrix of ERLA-4617 epoxy resin in an eight ply unidirectional configuration. This investigation produced stress-strain data, fracture loads, and fracture modes of the off-axis specimens.

Subsequently, to determine the effects on the fracture process, another series of experiments was conducted with angleplied [±θ]s configured specimens, where θ = 0°, 3°, 5°, 10°, 15°, 30°, 45°, 60°, 75°, and 90°. In addition to smooth specimens, notched samples were also prepared with both 0.25-in centered through-thickness slits and holes to determine: (1) the notch sensitivity of the composite structure, and (2) the effect, if any, of the notch type.

The 12- by 18-in angleplied panels were fabricated from Fiberite 1034E Prepreg (934 resin matrix with Thornel 300 graphite fibers). For the notch sensitivity analysis, all of the 2-in specimens were cut from the same panel (fig. 1) to insure that the fabrication technique, itself, did not become one of the factors affecting the composite fracture.

The specimens were incrementally loaded in unaxial tension until fracture occurred. Progressive fracture of these specimens was recorded by a unique facility developed at the Lewis Research Center known as Real-Time Ultrasonic C-Scan (RUSCAN). Depicted in figures 2 and 3, the RUSCAN facility consists of a microprocessor system, a monitor with 16-level gray scale reproduction capability, an ultrasonic signal conditioning system, and ultrasonic transducers in conjunction with a CGS 50 kip load frame (ref. 3).

The facility is unique in that the specimen is scanned while sustaining a load. At each load increment, a scan is taken which records the real-time damage occurring at the microstructural level. When viewed in sequence, the individual scans display the progressive damage in the fibrous composite.

Future experimental efforts include tensile testing of eight-ply unidirectional off-axis laminates. As an extension to the earlier work performed, these specimens will contain machined notches. Again, both slits and holes will be used to determine the notch sensitivity of these thicker laminates.

ANALYTICAL METHODS

As previously mentioned, the analytical methods used in modeling the progressive fracture of composites are incorporated into the CODSTRAN finite element computer code. The major elements comprising CODSTRAN are shown in the flow chart in Figure 4 and include: (1) Executive Module, (2) Input/Output Modules; (3) Analysis Module (ref. 4); (4) Composite Mechanics Module (ref. 5), and (5) Fracture Criteria Module (ref. 6).

CODSTRAN assesses composite durability in terms of defect growth/ progressive damage. Using one of two available combined-stress failure criteria, damage is determined on a ply-by-ply level for each finite element comprising a particular model. The iterative scheme employed is initiated with the application of a load to the finite element model. If intraply damage has occurred in any of the plies of an element, the stiffness coefficient for that element is reduced in the direction affected by the damage. When all plies in that element suffer damage (due to increased incremental loading) such that the element can no longer sustain a load, the element is considered destroyed and is purged from the finite element mesh. Thus damage is being predicted in a progressive manner until the iterations cease with the destruction of a sufficient number of elements which result in fracture.

In addition to determining the damage, CODSTRAN predicts the mode of fracture by registering the direction (longitudinal, transverse, or shear) of damage that occurred. CODSTRAN therefore provides a complete history of the failure process by predicting the progressive damage, the fracture load, and fracture mode.

CODSTRAN analyses were conducted in conjunction with the experimental investigations involving the angleplied ($[\pm\theta]_s$) laminates. Three finite element models were generated to represent the solid and notched (centered through-slit and centered through-hole) specimens. The mechanical, thermal, and hygral material properties of the prepreg are entered into the data bank. Environmental conditions such as the thermal and moisture conditions are also input parameters; thereby, demonstrating the versatility of the program and its capability to adequately model the physical composite specimen/structure.

Similarly, CODSTRAN will be used to analyze the off-axis laminates. One major difference in this study lies in the orientation of the 0.25-in through-slit. Since the plies are unidirectional it is desirable to orient the slit parallel to the fiber direction. This requires a generic-type model which can be rotated for the series of laminates involved. This model is currently being generated for the off-axis laminate studies.

FRACTURE SURFACE ANALYSIS

Thus far, in our attempt to characterize fracture, experimental data and predictive results have been generated. Another source of valuable information exists on the surfaces of the fractured graphite/epoxy specimens. The microstructural characteristics observed on the surfaces will be used in conjunction with the results, previously mentioned, to explain the failure process of graphite/epoxy laminates.

The majority of specimens fractured into two distinct puzzle-like pieces (fig. 5). Areas of particular interest exist on either side of the machined defects. To further investigate these areas, 0.75-in wide specimens were cut for the microscopic analysis using a diamond wheel, while carefully preserving the fractured surfaces from additional debris.

The specimens were mounted onto aluminum seats in preparation for the microscopic analysis. Using a vapor deposition process, the entire configuration was coated with a gold film approximately 200-Å thick to enhance the conductivity of the specimen and hence improve the transmission of the microscope.

Using the Amray 1200 Scanning Electron Microscope (SEM), at least one section from each fractured surface was observed at varying angles and magnifications. Particular attention was directed toward sections possessing extensive damage indicated by RUSCAN and/or CODSTRAN. Microstructural damage such as fiber fracture, matrix cracking, matrix hackling, and delaminations was observed and permanently recorded on Polaroid Type 52 film.

RESULTS AND DISCUSSION

This section summarizes the efforts from each discipline previously discussed. The outcome of the research including experimental data (RUSCAN), analytical solutions (CODSTRAN), photomicrographs (SEM), and the conclusions derived therefrom on the characteristics of composite fracture will be presented.

Photomicrographs were taken of the fractured surfaces of the off-axis Modmor I graphite/ERLA-4617 epoxy off-axis specimens in an effort to fulfill the objective of the project: to establish criteria that can be used to characterize fracture surfaces with respect to a predominant "single-stress" fracture mode (ref. 7). Thorough examination of the photomicrographs revealed that each fracture surface did indeed exhibit distinct morphological characteristics (figs. 6 and 7) which could be associated with a dominant fracture mode.

The angleplied ([±θ]s) Fiberite graphite/epoxy laminates were studied to determine the effect of ply orientation. It was observed that as the angle of the ply orientation increased with respect to the "X" axis, (which is coincident with a vertical axis and where +θ is measured clockwise and -θ is taken counter clockwise from this axis) the fracture load decreased. This result is evident from the data shown in tables I and II, which contain the experimentally determined fracture loads and the CODSTRAN predicted fracture loads, respectively. Note, that for the unnotched specimens, the experimental and CODSTRAN fracture loads are in good agreement.

When considering the notch sensitivity of the composite, the experimental results indicate that in terms of ultimate strength, the presence of a notch had little effect. CODSTRAN fracture load predictions, however, were conservative in comparison, indicating notch sensitivity. This disparity is in part due to the excessive predicted stress concentrations at the defect (slit/hole) edge. Though not completely determined at this time, it appears that the stress concentration does not occur. Currently, modifications are being incorporated into the CODSTRAN code to determine the exact nature of the problem.

In addition, both the experimental and CODSTRAN fracture loads indicate that the type of notch is not a factor affecting the composite fracture. The microstructural characteristics on the surfaces of select specimens support this conclusion because the damage observed on the surface of the unnotched specimen is similar to that observed on the notched fracture surfaces.

Figure 8 depicts the microstructural damage in four ply unidirectional specimens, including fiber pull-out and a tiered fracture surface. In figure 9, the damage observed on all the surfaces of the [±45]s specimens is identical and consists of a combination of tiered and flat morphology along with fiber pull-out and extensive matrix hackles. These observations demonstrate the use of post failure analysis in corroborating the experimental (RUSCAN) results for both unidirectional and angleplied laminates.

As discussed earlier, CODSTRAN also has the capability of predicting fracture modes based on progressive damage and the direction in which damage occurs. Figures 10, 11, and 12 depict the progressive damage of [±15]s graphite/epoxy specimens including unnotched, notch/slit, and notch/hole respectively. In comparing the meshes for the notched specimens, note that the damage patterns are almost identical, indicating insensitivity to notch type.

The entire set of angleplied specimens was tested using the RUSCAN facility which monitors and records progressive damage. Output is a 16-level full gray scale image of the digitized ultrasonic signal. A typical RUSCAN output is shown in figure 13. These real-time damage images were then compared with CODSTRAN results. Figure 14 shows the excellent correlation which exists not only for this particular [±45]s specimen, but for the majority of the specimens tested.

Having established confidence in CODSTRAN's predictive capability, analyses were performed to establish the fracture mode of the angleplied laminates. Four predominant fracture modes -- longitudinal tensile, intraply shear, interply delamination, and transverse tensile -- were predicted and are shown in table III. One obvious characteristic observed from the table is that the mode of fracture is a function of the ply configuration.

It was at this time that a section from each fracture surface was examined to document the microstructural characteristics and establish criteria relating these characteristics to a dominant fracture mode. The type of behavior indicated by CODSTRAN was verified with the microscopic analysis: that the predominant fracture mode is a function of ply orientation. Specifically, for lower angleply laminates ($[0]_4$ - [±15]s) fracture is the result of a longitudinal tensile mode characterized by a tiered surface, fiber pull-out and fiber breakage. Laminates with a lay-up of [±30]s - [±45]s fracture from the combined effect of longitudinal tensile and intralaminar shear modes characterized by both tiered and level surfaces, fiber pull-out and breakage, and an abundant amount of matrix hackles. The cause of fracture in laminates with a higher angleply orientation ([±60]s - $[90]_4$) is the transverse tensile mode characterized by level surfaces, matrix cleavage, and matrix cracking. The typical microstructural characteristics observed are shown in figure 15.

The complete documentation of the microscopic analysis is included in reference 8. From the analysis, table IV was derived. The observed fracture modes are in good agreement with the CODSTRAN predicted modes. Note, that due to the violent actions occurring in the fracture region at the time of failure, it is difficult to discern interply delamination as a failure mode. Nonetheless, the data provided from the post-failure analysis are a valuable source of information in both the verification of analytical results and in the development of a data base for post-fracture analysis.

CONCLUSIONS

In characterizing the fracture of graphite/epoxy composites, several methods of analysis were utilized. The experimental and RUSCAN facilities, the CODSTRAN computer code, and the post fracture microscopic investigation are independently effective techniques to study composite fracture. In combination, however, the ability to study progressive fracture and all the many factors which affect it is synergistically enhanced. Use of the fractographic results in verifying previously established experimental and analytical results is of particular importance in that it has enhanced the level of confidence in the predictive capabilities of CODSTRAN which is proving to be a valuable tool in the determination of composite durability.

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4. McCormick, C.W., ed.: NASTRAN User's Manual (level 15). NASA SP-222(01), 1972.

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8. Ginty, C.A.; and Irvine, T.B.: Fracture Surface Characteristics of Notched Angleplied Graphite/Epoxy Composites. NASA TM-83786, 1984.

TABLE I. - FRACTURE LOADS (LB) OF $[\pm\theta]_s$ G/E LAMINATES (DETERMINED EXPERIMENTALLY)

Notch type	Ply configuration: $[\pm\theta]_s$; θ in degrees									
	0	3	5	10	15	30	45	60	75	90
Unnotched--solid	8060	6500	5200	4500	3700	2620	900	420	220	260
Notched--thru slit	7820	5500	4940	4160	2750	2150	880	320	180	180
Notched--thru hole	6000	5720	4700	4240	3300	1750	950	360	220	120

TABLE II. - FRACTURE LOADS (LB) OF $[\pm\theta]_s$ G/E LAMINATES (PREDICTED BY CODSTRAN)

Notch type	Ply configuration: $[\pm\theta]_s$; θ in degrees									
	0	3	5	10	15	30	45	60	75	90
Unnotched--solid	8300	7400	6950	5000	4400	2150	900	400	200	200
Notched--thru slit	4500	3950	3600	2850	2250	1000	425	300	175	150
Notched--thru hole	4700	3850	3500	2700	2150	1100	425	200	150	100

TABLE III. - FRACTURE MODES[a] OF $[\pm\theta]_s$ G/E LAMINATES (PREDICTED BY CODSTRAN)

Notch type	Ply configuration: $[\pm\theta]_s$; θ in degrees									
	0	3	5	10	15	30	45	60	75	90
Unnotched--solid	LT	LT S[3]	LT S[3]	LT S[3]	I S	S	I S	TT	TT	TT
Notched--thru slit	LT S[1]	LT S	LT S	S	S	I S	I S	I TT S[2]	TT	TT
Notched--thru hole	LT S	LT S	LT S	S	S LT	I S	I S TT	I TT	TT	TT

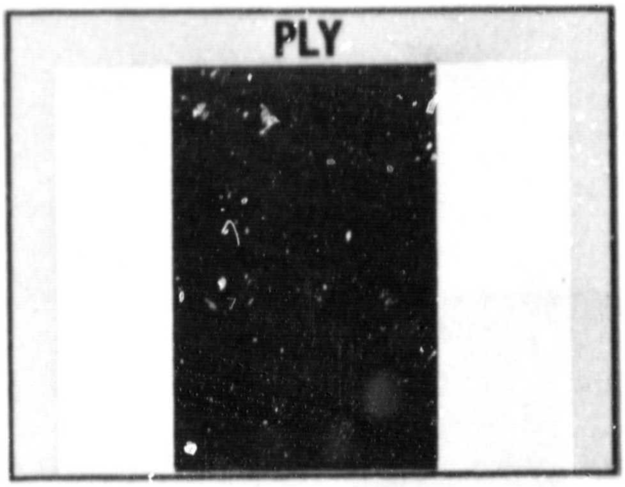
[a]LT = Longitudinal tension
TT = Transverse tension
S = Intraply shear:
1) Intraply shear occurring around notch tip during progressive fracture
2) Minimal intraply shearing during fracture
3) Some intraply shear occurring near constraints (grips)

I = Interply delamination

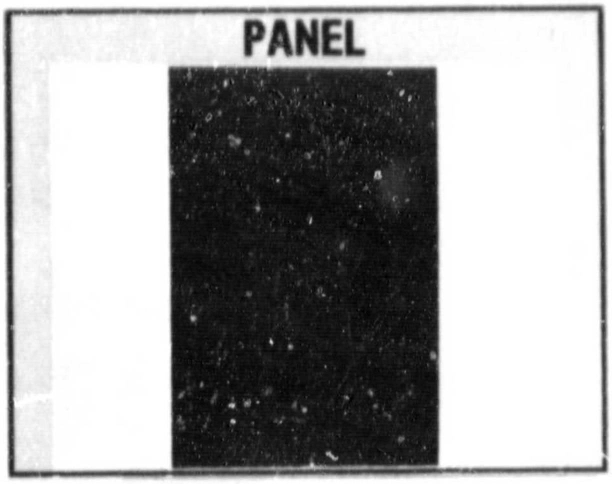
TABLE IV. - FRACTURE MODES[a] OF $[\pm\theta]_s$ G/E LAMINATES (DETERMINED BY SEM ANALYSIS)

Notch type	Ply configuration: $[\pm\theta]_s$; θ in degrees									
	0	3	5	10	15	30	45	60	75	90
Unnotched--solid	LT	LT S	LT S	LT S	LT S	LT S	S LT	TT S	TT	TT
Notched--thru slit	LT S	LT S	LT S	LT S	LT S	LT S	S LT	TT S	TT	TT
Notched--thru hole	LT S	LT S	LT S	LT S	LT S	LT S	S LT	TT S	TT	TT

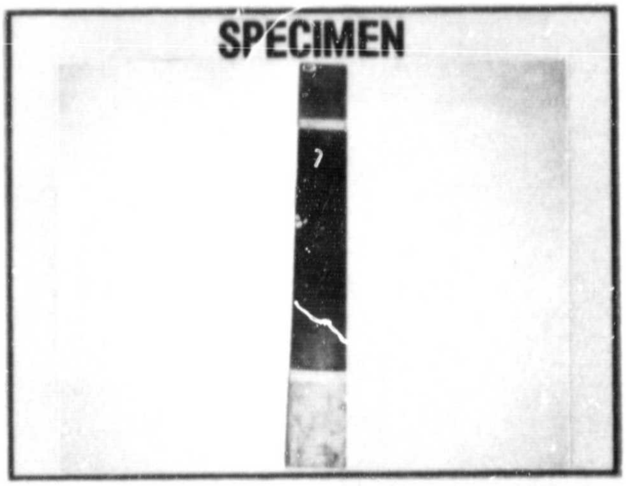
[a]LT = Longitudinal tension
TT = Transverse tension
S = Intraply shear



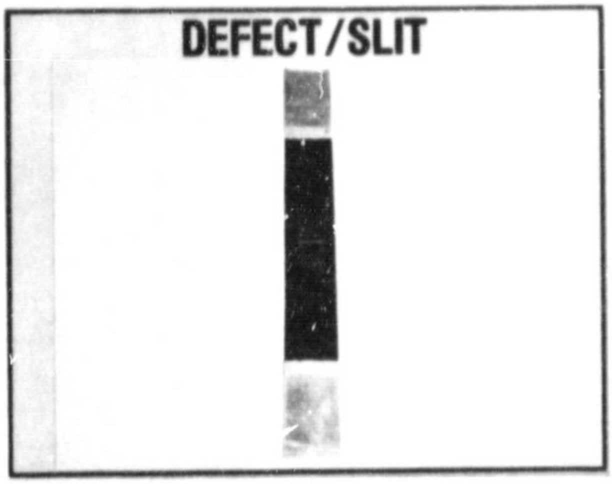
Step 1; Fiberite 934 prepreg; T 300 graphite fiber.



Step 2; 4 plies cured at 350° for 2.5 hours.



Step 3; specimen dimensions: 18. X 2. X .02 inches; machined with diamond tipped cutting wheel; beveled aluminum tabs.



Step 4; slit dimensions: 0.25 X 0.05 inches; notching by ultrasonic abrasive slurry.

Figure 1. - Specimen fabrication procedure for graphite/epoxy angleplied laminates with a centered notch (slit).

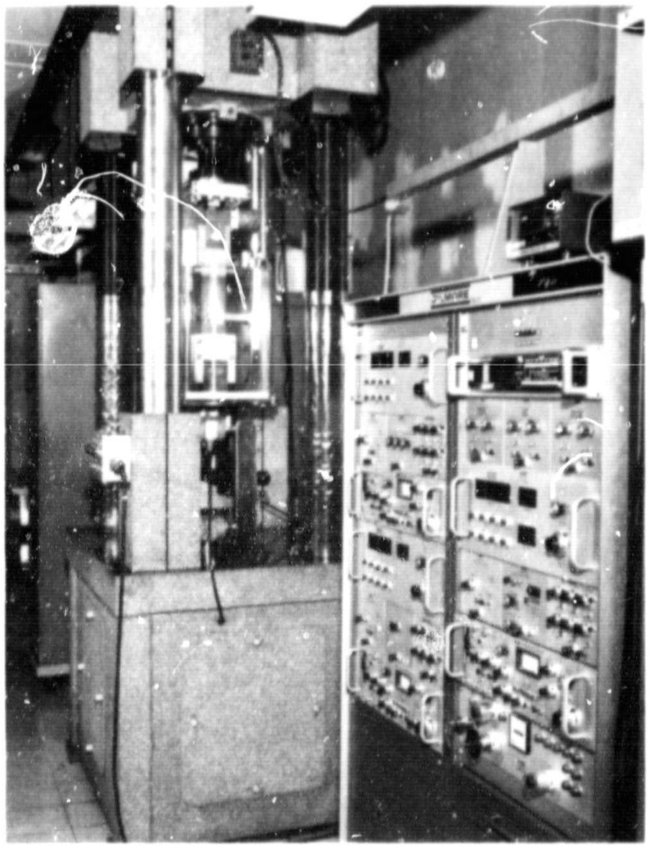


Figure 2. - Load frame used for testing of uniaxial composite tension specimens with ultrasonic transducers mounted on the frame.

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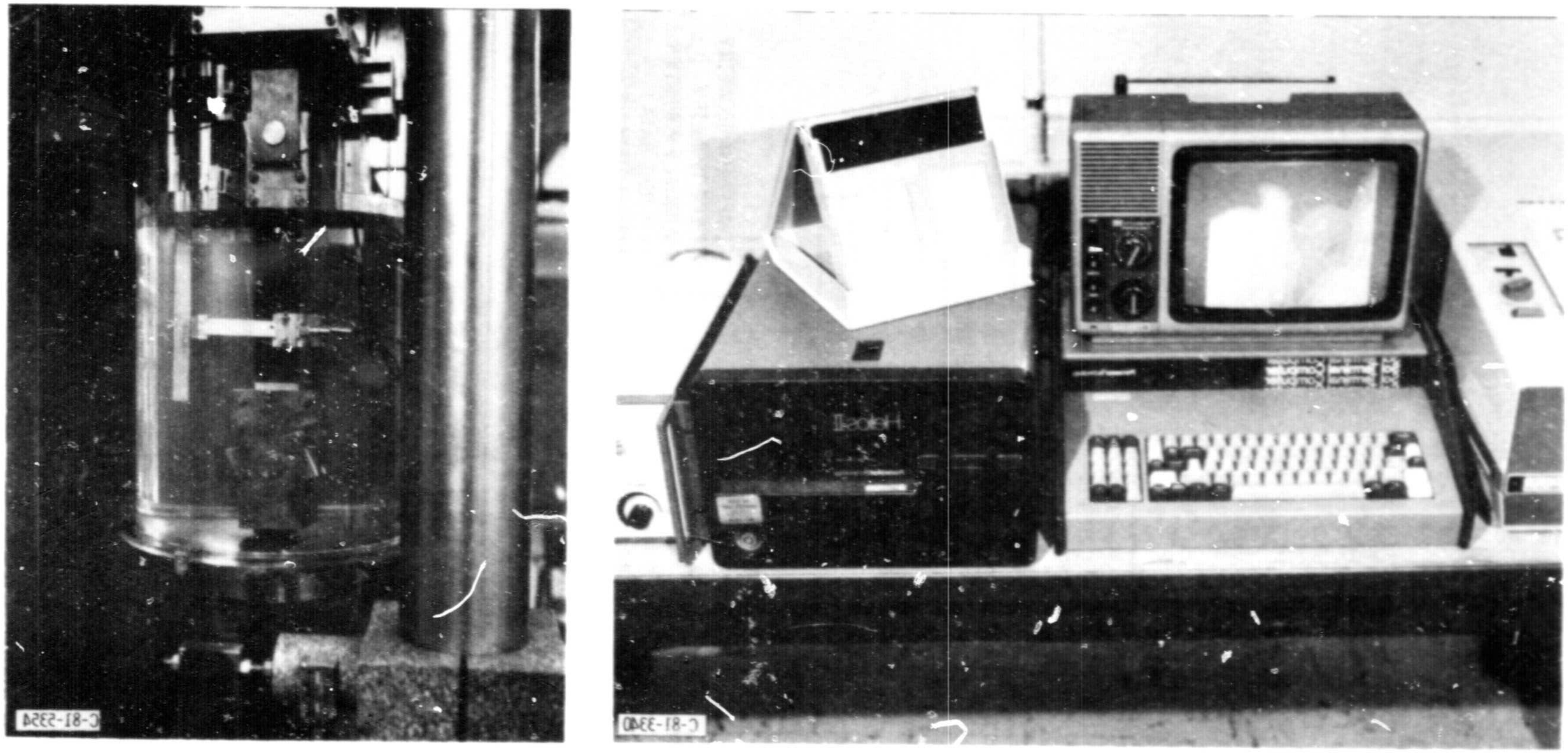


Figure 3. - The Real-Time Ultrasonic C-Scan (RUSCAN) facility. From left, the disk based microcomputer test rig control and data acquisition system, and the ultrasonic transducers in the waterbucket with a notched composite specimen in grips on the load frame.

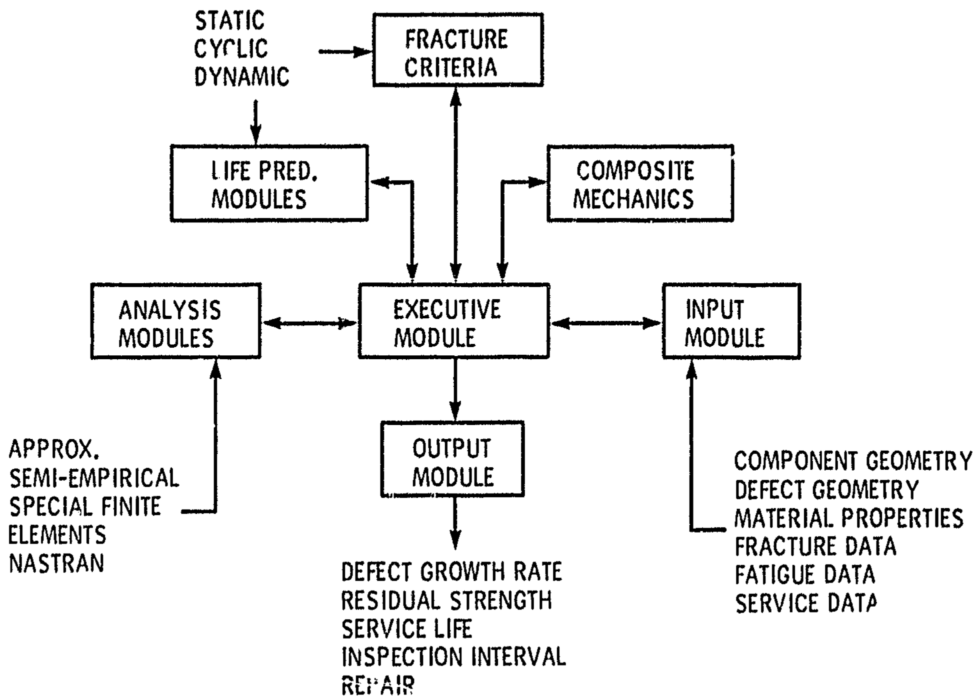
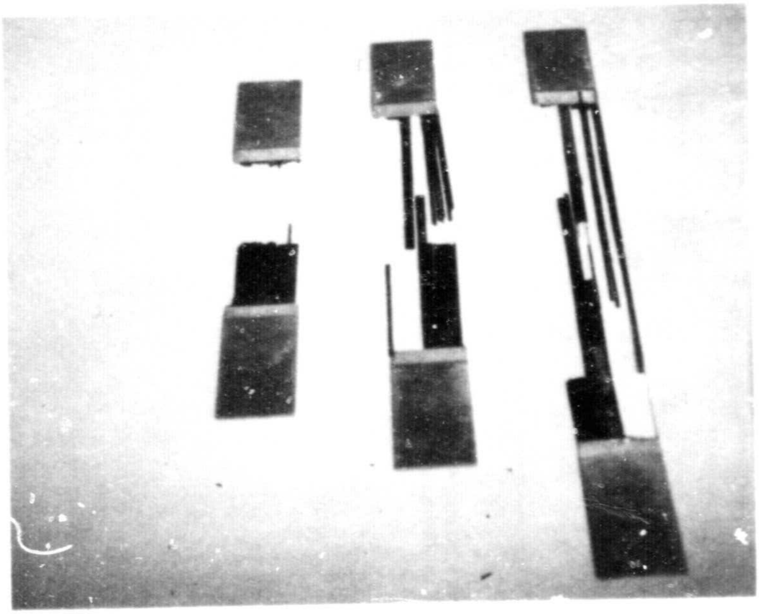
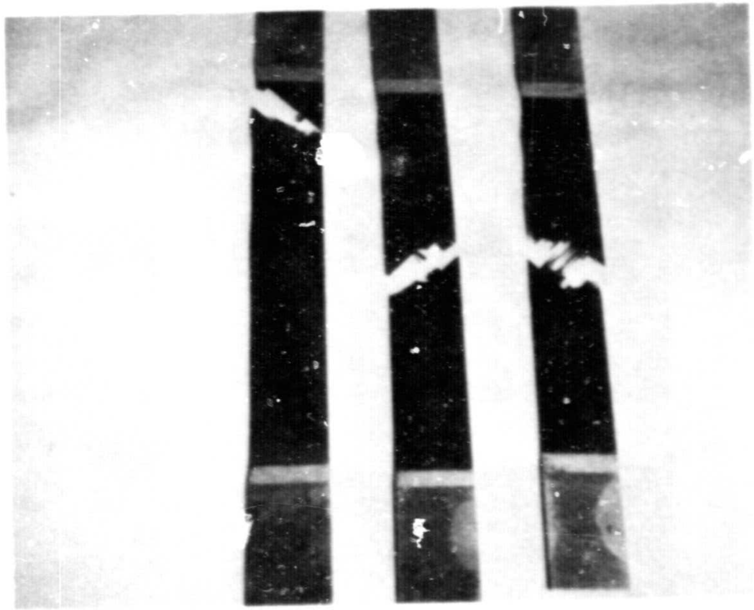


Figure 4. - CODSTRAN flow-chart.

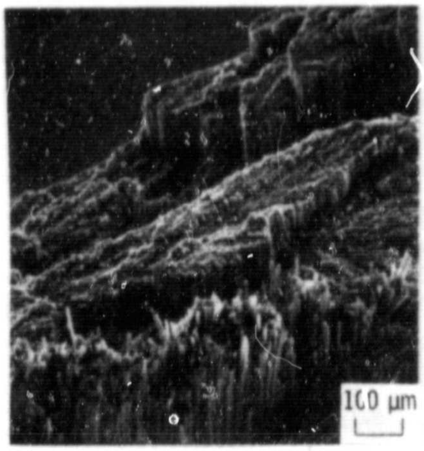


(a) unidirectional.

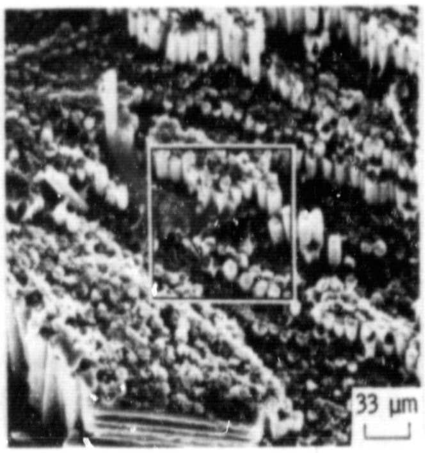


(b) [±45]s.

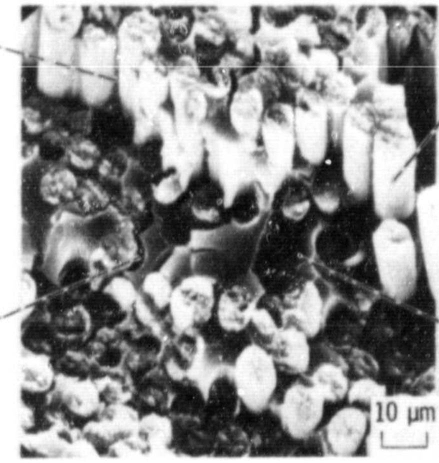
Figure 5. - Fractured G/E specimens from left to right -- solid, notch/slit and notch/hole.



(a) General view.

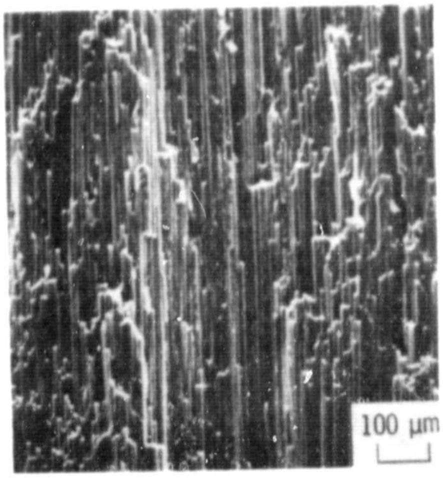


(b) Detailed view.

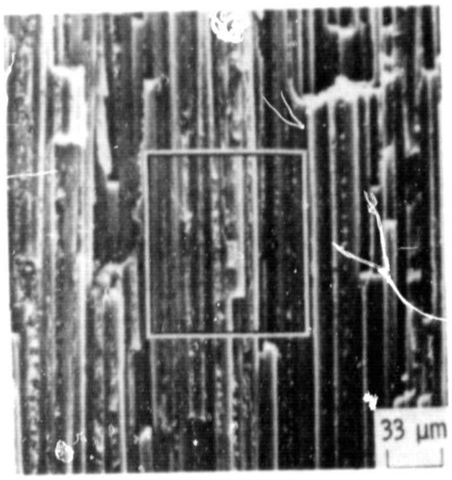


(c) Enlargement of detail in (b) to show fracture mode.

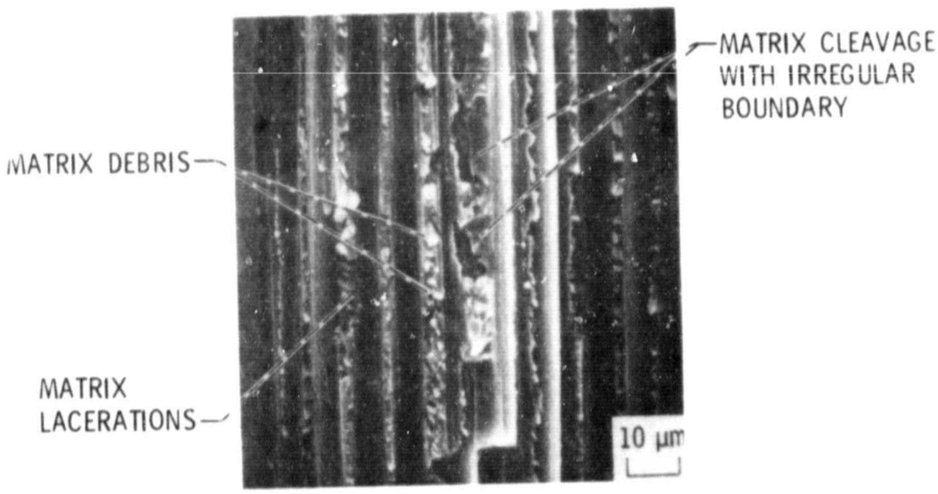
Figure 6. - Microstructural characteristics of fractured surface of MOD I/Epoxy unidirectional composite associated with a longitudinal tensile fracture mode.



(a) General view.

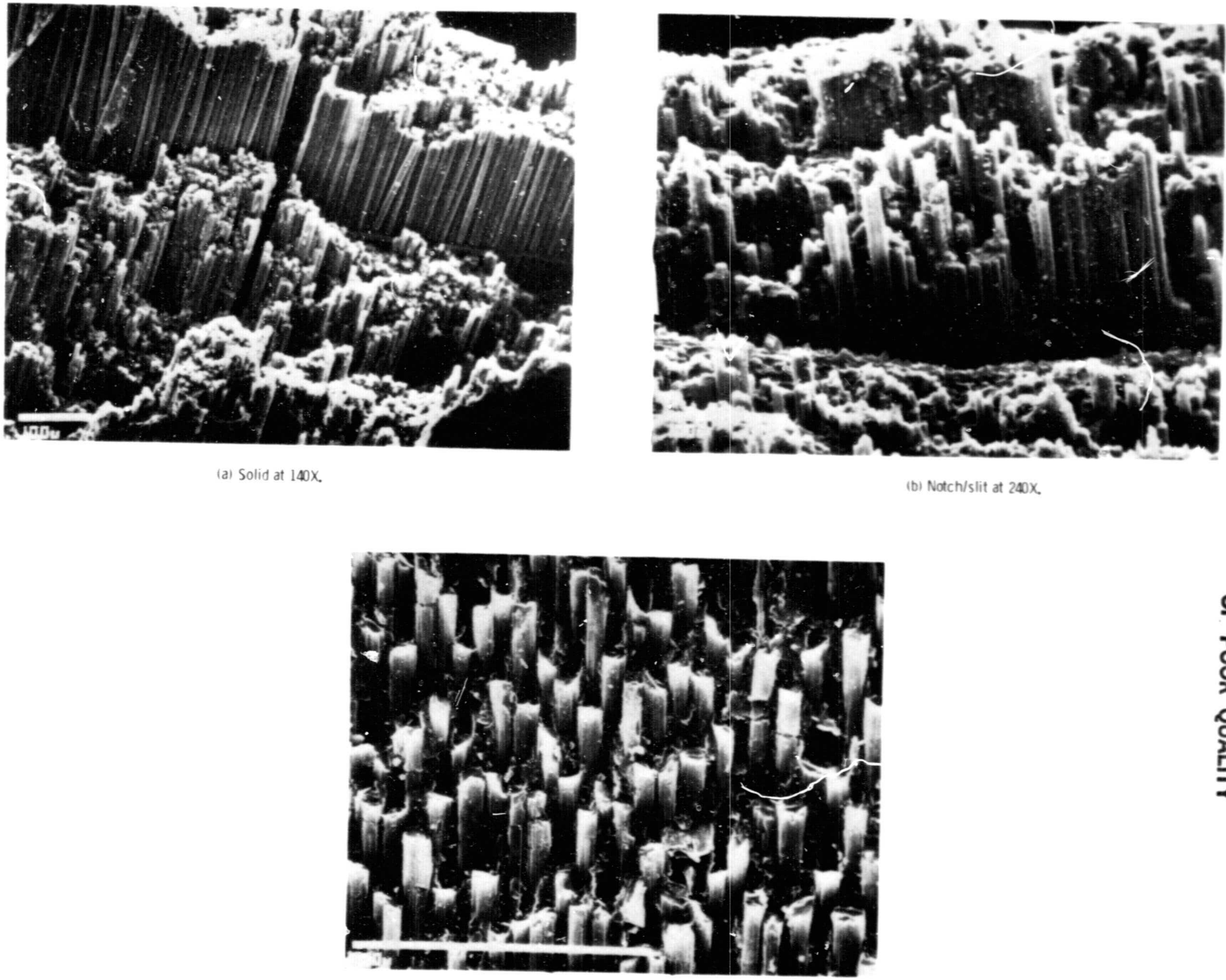


(b) Detailed view.



(c) Enlargement of detail in (b) to show fracture mode.

Figure 7. - Microstructural characteristics of fractured surface of MOD I/Epoxy unidirectional composite tested at 45 degrees associated with a mixed mode fracture.



(a) Solid at 140X.

(b) Notch/slit at 240X.

(c) Notch/hole at 250X.

Figure 8. - The microstructural fracture surface characteristics of the unidirectional G/E laminate.

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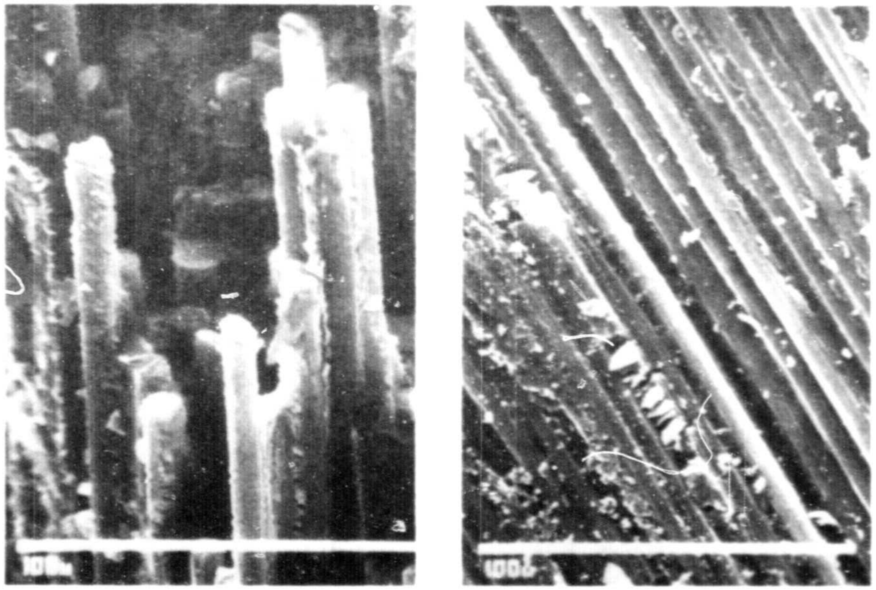
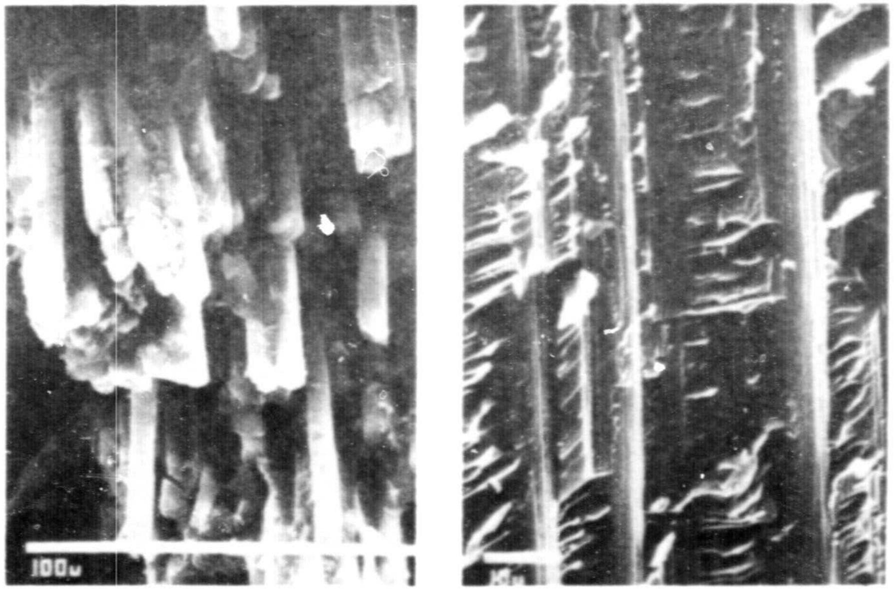
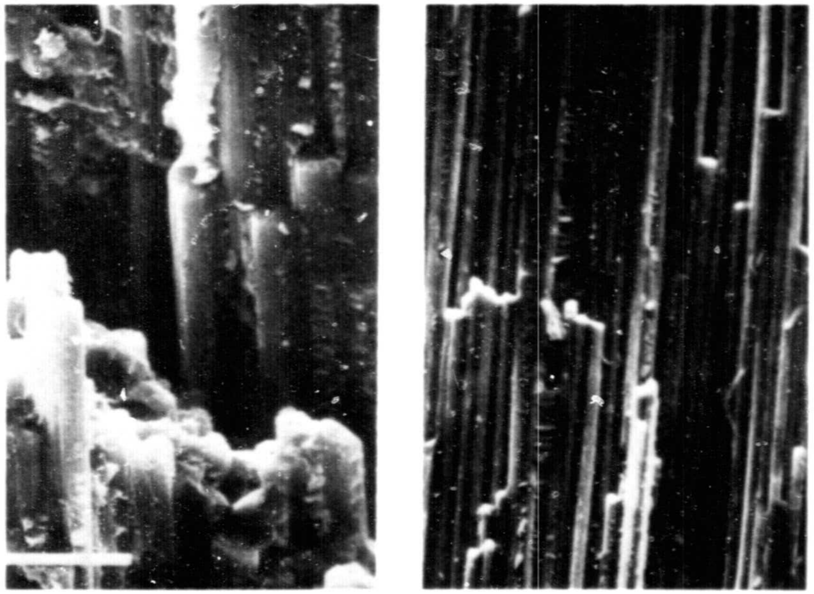


(a) Solid specimen at 710X / 560X.

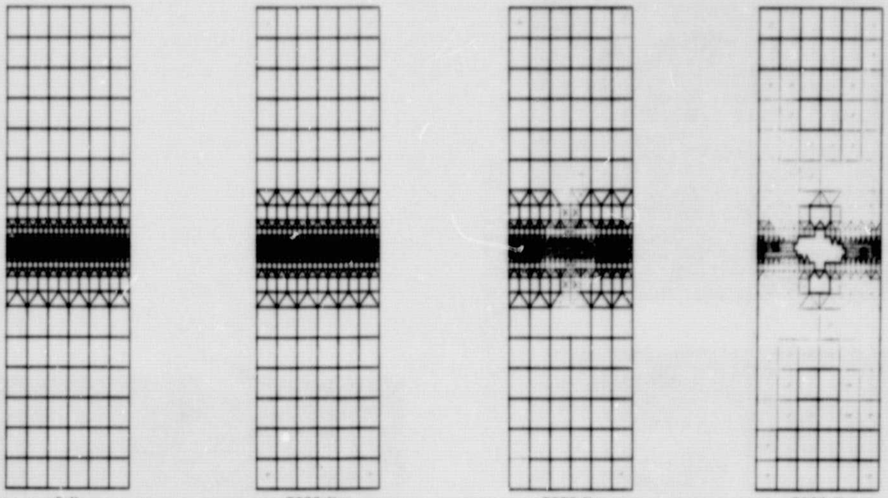


(b) Notch/slit specimen at 600 X / 1200 X.



(c) Notch/hole specimen at 730X / 200X.

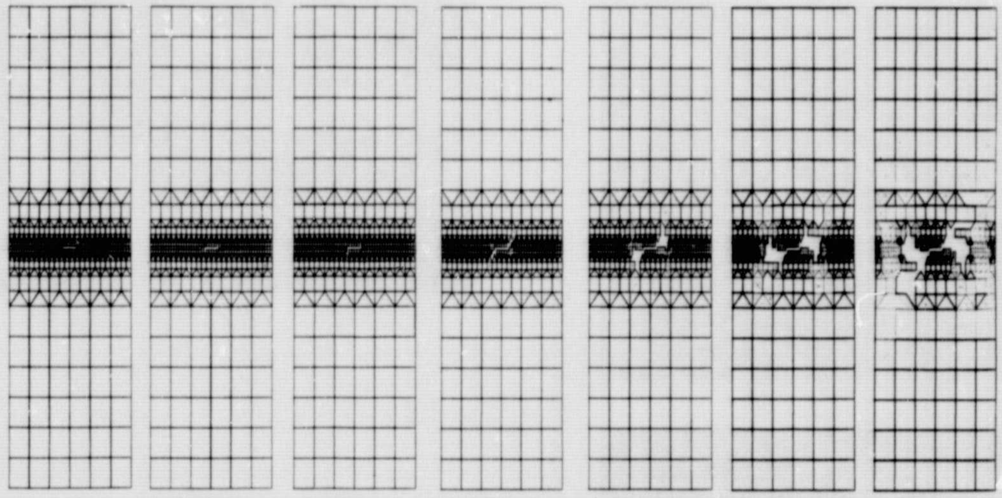
Figure 9. - Fracture surface charateristics of the [$\pm$ 45]s G/E laminate.



LOAD: 0 lb 5000 lb 5000 lb 5000 lb

ORIGINAL MESH: ELEMENTS 540
NODES 446
DEGREES OF FREEDOM 871

Figure 10. - CODSTRAN determined successive damage extent and defect growth as a result of progressive fracture in a $[\pm 15]_s$ graphite/epoxy solid laminate. Finite elements marked with a '+' denote damaged elements and those marked with an 'X' denote destroyed elements.



LOAD: 0 lb 2350 lb 2350 lb 2350 lb 2350 lb 2350 lb 2350 lb

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DEGREES OF FREEDOM 871

Figure 11. - CODSTRAN determined successive damage extent and defect growth as a result of progressive fracture in a $[\pm 15]_s$ graphite/epoxy laminate with a 0.25 in. by 0.05 in. centered through-slit. Finite elements marked with a '+' denote damaged elements and those marked with an 'X' denote destroyed elements.

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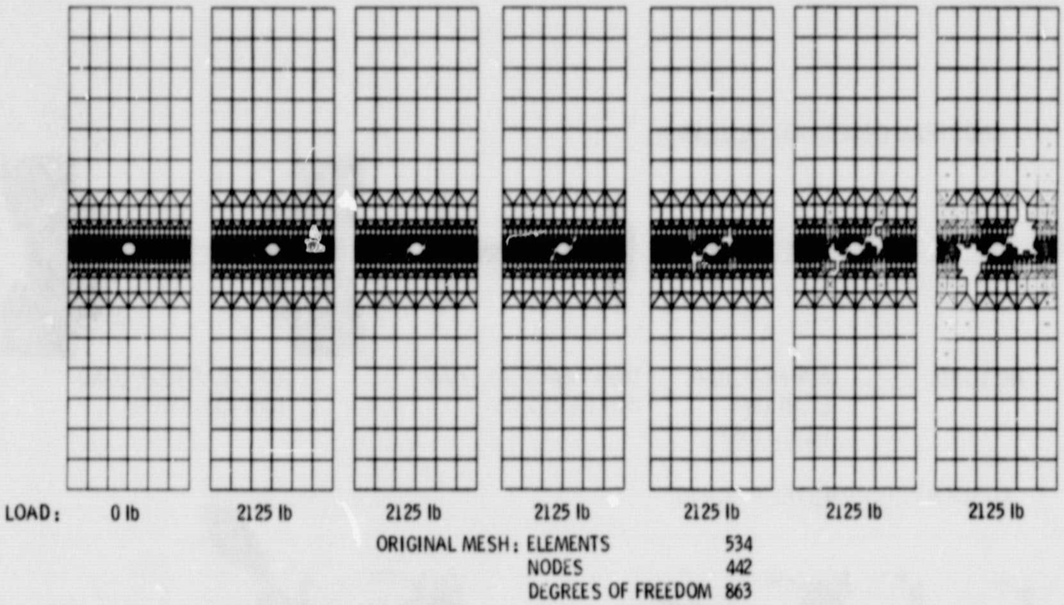


Figure 12. - CODSTRAN determined successive damage extent and defect growth as a result of progressive fracture in a$[\pm 15]_s$ graphite/epoxy laminate with a 0.25 in. diameter centered through-hole. Finite elements marked with a '+' denote damaged elements and those marked with an 'X' denote destroyed elements.

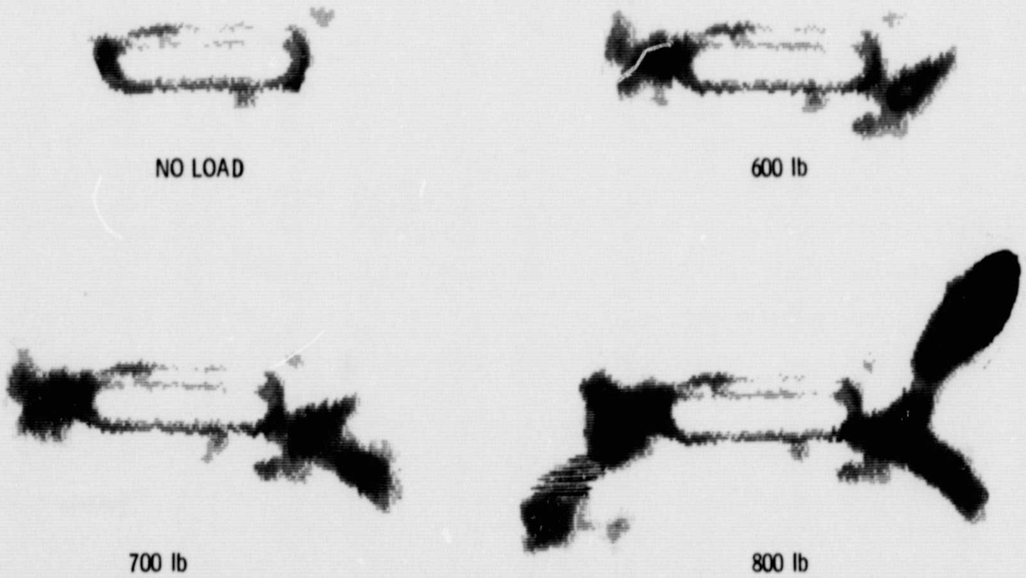


Figure 13. - C-Scan images of the $[\pm 45]_s$ laminate reveal an increase in delaminations at the tip of the notch/slit as the load increment increases until final fracture occurs at 880 lb.

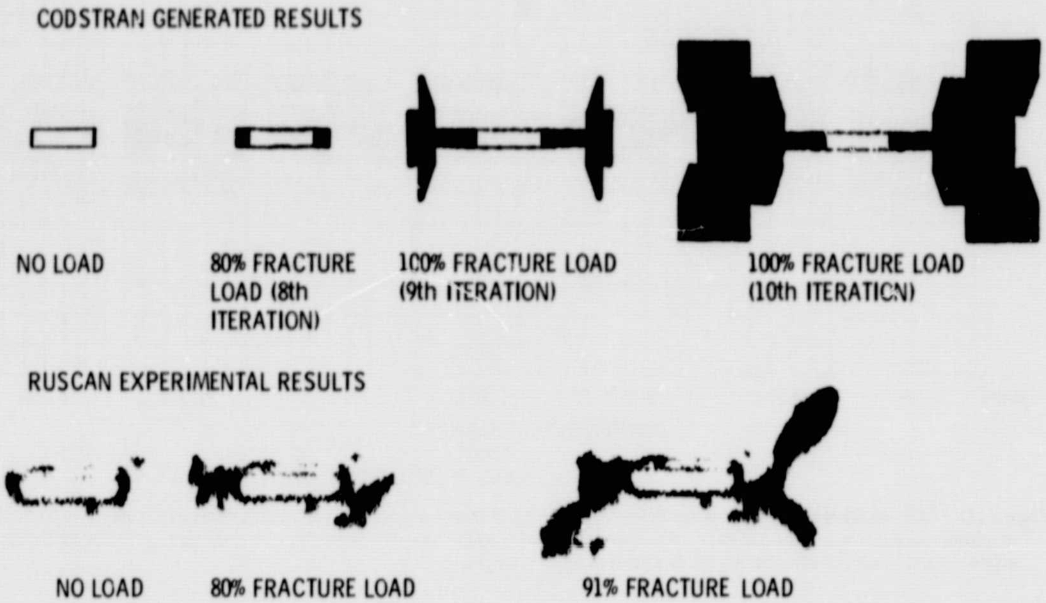
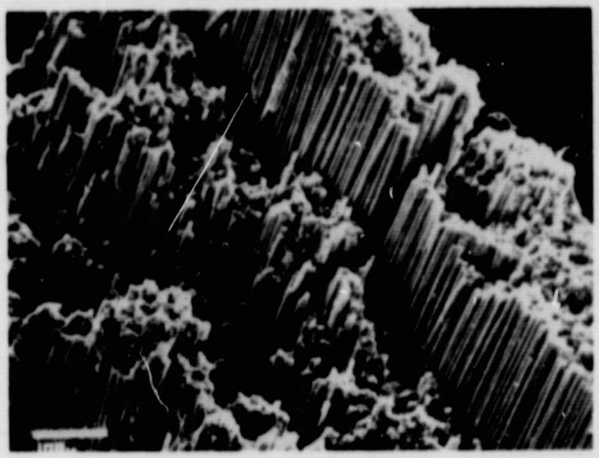
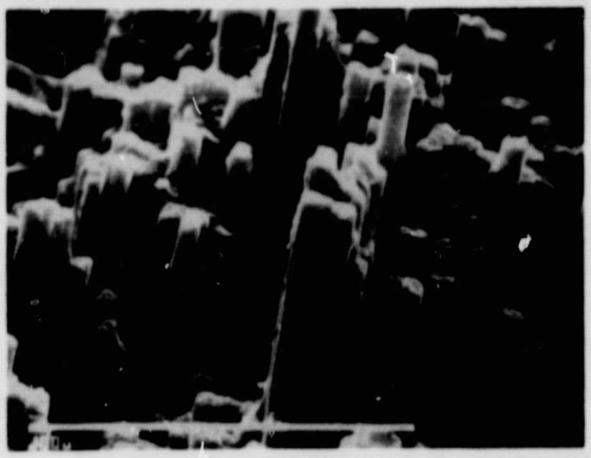


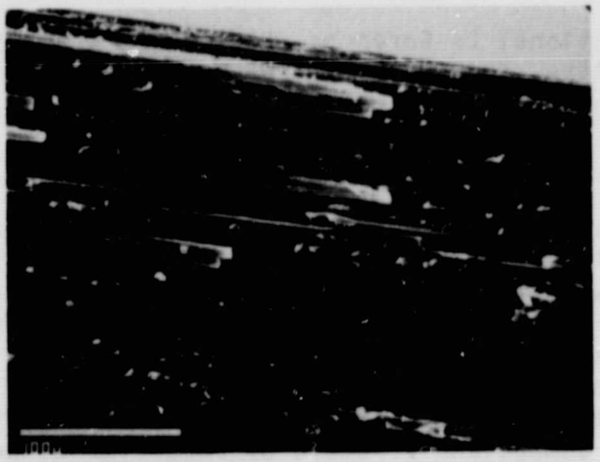
Figure 14. - Progressive fracture of a $[\pm 45]_s$ laminate. Results shown are for a 2 in. wide tension specimen with a 0.25 x 0.05 in. centered slit.



(a) Longitudinal tensile fracture characterized by a tiered surface caused by fiber fracture.



(b) Intralaminar shear fracture characterized by a surface with extensive matrix hackling.



(c) Transverse tensile fracture characterized by smooth fiber surfaces with some apparent matrix cleavage.

Figure 15. - Typical fracture surfaces from unidirectional and angleplied graphite/epoxy composite laminates.

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15. Supplementary Notes

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16. Abstract

Lewis Research Center is involved in the development of computational mechanics methods for predicting the structural behavior and response of composite structures. In conjunction with the analytical methods development, experimental programs including post failure examination have been conducted to study various factors affecting composite fracture such as laminate thickness effects, ply configuration, and notch sensitivity. Results have indicated that the analytical capabilities incorporated in the CODSTRAN computer code are effective in predicting the progressive damage and fracture of composite structures. In addition, the results being generated are establishing a data base which will aid in the characterization of composite fracture.

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